

Dust in Interstellar Clouds, Evolved Stars and Supernovae

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Abstract. Outflows of pre-main-sequence stars drive shocks into molecular material within 0.01 - 1 pc of the young stars. The shock-heated gas emits infrared lines of H_2 and H_2O and millimeter and submillimeter lines of many species including CO , SiO , H_2S and HCO^+ . Dust grains are important charge carriers and play a large role in coupling the magnetic field and flow of neutral gas. Some understanding of the effects of the dust on the dynamics of oblique shocks began to emerge in the 1990s. However, detailed models of these shocks are required for the calculation of the grain sputtering contribution to gas phase abundances of species producing observed emissions. We are developing such models.

Some of the molecular species introduced into the gas phase by sputtering in shocks or by thermally driven desorption in radiatively heated hot cores form on grain surfaces. Recently laboratory studies have begun to contribute to the understanding of surface reactions and thermally driven desorption important for the chemistry of star forming clouds.

Dusty plasmas are prevalent in many evolved stars just as well as in star forming regions. Radiation pressure on dust plays a significant role in mass loss from some post-main-sequence stars. The mechanisms leading to the formation of carbonaceous dust in the stellar outflows are similar to those important for soot formation in flames. However, nucleation in oxygen-rich outflows is less well understood and remains a challenging research area.

Dust is observed in supernova ejecta that have not passed through the reverse shocks that develop in the interaction of ejecta with ambient media. Dust is detected in high redshift galaxies that are sufficiently young that the only stars that could have produced the dust were so massive that they became supernovae. Consequently, the issue of the survival of dust in strong supernova shocks is of considerable interest.

Keywords: interstellar dust; hydromagnetic shocks; interstellar chemistry; star formation; AGB and post-AGB stars; supernovae

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INTRODUCTION

The claim that “The presence of dust particles implies that the physical state of such a medium may be somewhat different than that discussed in the classical work by Eddington, in which only atoms were assumed to be abundant” appears prominently on the first page of Spitzer’s important May 1941 paper [1]. In it Spitzer showed how to calculate the average charge on an interstellar dust grain. The field of dusty astrophysical plasmas has existed for close to seven decades. Here we describe some studies in a few areas of dusty astrophysical plasmas beyond the Solar System.

SHOCKS IN MAGNETIZED STAR FORMING REGIONS

Stars form in regions in which the number density of hydrogen molecules is at least 10^4 cm^{-3} . Grains with a range of sizes between about 10 and 100 nm contain roughly one percent of the mass. The fractional ionizations are 10^{-7} and lower. Grains are negatively charged and their collisions with neutrals are important in coupling neutral species to the magnetic field. Two-fluid [2] and multifluid models of shocks driven into star forming regions by outflows of the young stars have been constructed for more than 25 years.

In such models of perpendicular shocks with speeds of less than about 40 km s^{-1} , the flows in all fluids are continuous and charged species are accelerated earlier than neutrals, leading to dissipation regions that are large compared to the mean free path. Many researchers have used a rather crude treatment of the dynamics of charged species in such shocks. In fact, dust grains in each of a number of size ranges and charged states, electrons and gas phase ions should be treated as distinct fluids [3,4].

Wardle [5] showed that in a steady multifluid hydromagnetic model of a fast-mode oblique shock, integration in the downstream direction does not reach the downstream state because it corresponds to a saddle point. In some cases, local equilibrium may not obtain everywhere, and integration in the upstream direction is not always appropriate. Falle [6] performed the first time-dependent study of plane-parallel, oblique shocks in which the dynamics of all grain and gas phase species are treated rigorously, and all three components of the current are calculated. Like Wardle [5], Falle [6] made simple assumptions about the fractional ionization and charges and temperatures of the various species. We are including a more thorough treatment of these quantities similar to that of Pilipp et al. [3]. This is necessary for the calculation of dust sputtering rates [7] important for the interpretation of molecular line data.

Future models of evolving dense cores should include at least two grain fluids even when strong shocks are not present.

SURFACE PROCESSES IN STAR FORMING REGIONS

Most gas phase species more massive than helium deplete onto dust grains in 10 K objects, called dense cores, that are the precursors of stars. For a molecular hydrogen number density of 10^5 cm^{-3} , the depletion time is roughly 10^5 years which is comparable to the free fall time. Many species accreted onto the dust grains react with one another creating hydrogenated species like water and methane and some more complicated molecules including methanol. The chemistry on the surfaces and the mechanisms that desorb species are important because they affect the gas phase abundances of molecules observed to probe the dynamics of star formation. Desorption can be driven thermally which is particularly important in hot cores, which have temperatures of 10^2 K , in regions where the birth of massive stars occurs. It can also be induced by the absorption of photons [8,9], some of which cosmic rays produce [10], and by exothermic reactions [11].

A lack of detailed knowledge of binding energies and surface sweeping rates of many species and of many reaction barriers hinders the study of the grain surface chemical kinetics. It is made even more difficult by the fact that usually only a small number of

reactive molecules are on a grain's surface, causing standard rate equation treatments to be inappropriate. Green et al. [12] adopted a master equation approach to study surface chemistry, but it is too expensive computationally for most cases. Barzel and Biham [13] have introduced a treatment based on the solution of moment equations derived from the master equation. It is computationally tractable for systems of interest.

Williams et al. [14] have reviewed theoretical and laboratory work on H_2 formation on surfaces. Recent studies have provided the first insight into the internal excitation of H_2 upon formation on and escape from surfaces. Some laboratory results on excitation were achieved through the use of state selective laser induced ionization. Theorists have investigated the internal excitation of H_2 when it is formed by the Eley-Rideal and Langmuir-Hinshelwood mechanisms. The first involves the reaction of an atom just approaching the encountered surface and reacting with a chemisorbed atom. The second involves the reaction between two physisorbed atoms which sweep the surface.

Williams et al. [14] have also reviewed recent work on laboratory studies of adsorption and desorption on surfaces. The combination of reflection absorption infrared spectroscopy (RAIRS) and temperature programmed desorption (TPD) have enabled the development of a multi-step picture of the carbon monoxide from a mixture of carbon monoxide and water ices on surfaces. If the initial ice thickness is less than 1 nm, as the temperature increases, CO desorbs at four distinct temperatures. RAIRS is being used to study the yields of reactions on mimics of interstellar grain surfaces.

DUST FORMATION IN AGB STARS

Asymptotic Giant Branch stars burn helium and hydrogen in shells surrounding carbon-oxygen cores. An AGB star's luminosity can approach 10^4 that of the Sun and peaks in the red. Its atmosphere extends to about an AU. Mass loss from an AGB star is driven by stellar pulsations and radiation pressure on dust grains, and mass loss rates reach up to 10^{-4} solar masses per year. The outflow speeds are 20 to 40 km s⁻¹. M-type AGB stars have the most oxygen-rich atmospheres. S-type AGB stars are more evolved, and their atmospheres contain elements produced by s-process nuclear burning and dredged up from lower layers. C-type AGB stars are even more evolved and have carbon-rich atmospheres. Ferrarotti and Gail [15] have modelled dust production in AGB stars as they evolve from M-type to C-type. Dust forms in regions in which the number density of hydrogen nuclei is 10^9 cm⁻³.

Cherchneff [16] summarized the mechanisms leading to the formation of carbonaceous dust grains in carbon-rich stars. Reactions of simple species with acetylene and with atomic hydrogen initiate the formation of ring molecules. Subsequent reactions result in the generation of PAHs. Coagulation of PAHs occurs, and platelets emerge and then join together to produce soot-like particles.

Dust generation in oxygen-rich environments is a more challenging problem and was reviewed in 2004 by Patzer [17]. He noted that "In contrast to e. g. polyaromatic hydrocarbons (PAHs) *no general building principles or schemes are known for small oxide clusters.*" Thus, searches for the minimum energy configurations, based on the solution of Schroedinger's equation, for various combinations of atoms have been made in order to identify stable cluster configurations. However, full quantum chemical treatments

cannot be used for large systems. Consequently, semiempirical interaction potentials have sometimes been employed. In recent studies of MgO clusters, Bhatt and Ford [18] have used a combination of the compressible ion model and the polarizable ion model to calculate interionic potentials.

The level of uncertainty that remains in this area is sufficient that Nuth and Ferguson [19] felt compelled to entitle a paper “Silicates Do Nucleate in Oxygen-Rich Outflows: New Vapor Pressure Data for SiO”.

DUST IN SUPERNOVAE

Sugarman et al. [20] argued that up to 0.02 solar masses of dust formed in Type II supernova 2003gd. Nozawa et al. [21] showed that the survival of such dust as the ejecta pass through the reverse shock depends on the supernova’s energy, the dust particle size and the properties of the envelope retained by the precursor star. They found that for some reasonable sets of parameters the fraction, by mass, of the dust produced in the ejecta that survives the reverse shock is as high as 0.8.

REFERENCES

1. L. Spitzer Jr., *Astrophys. J.* 93, 369-379 (1941).
2. B. T. Draine, W. G. Roberge and A. Dalgarno, *Astrophys. J.* 264, 485-507 (1983).
3. W. Pilipp, T. W. Hartquist and O. Havnes, *Mon. Not. R. astr. Soc.* 243, 685-691 (1990).
4. W. Pilipp and T. W. Hartquist, *Mon. Not. R. astr. Soc.* 267, 801-810 (1994).
5. M. Wardle, *Mon. Not. R. astr. Soc.* 298, 507-524 (1998).
6. S. A. E. G. Falle, *Mon. Not. R. astr. Soc.* 344, 1210-1218 (2003).
7. P. Caselli, T. W. Hartquist and O. Havnes, *Astron. Astrophys.* 322, 296-301. (1997).
8. D. A. Williams, T. W. Hartquist and D. C. B. Whittet, *Mon. Not. R. astr. Soc.* 258, 599-601 (1992).
9. K. I. Oberg et al., *Astrophys. J.* 662, L23-L26 (2007).
10. S. S. Prasad and S. P. Tarafdar, *Astrophys. J.* 267, 603-609 (1983).
11. R. T. Garrod, V. Wakelam and E. Herbst, *Astron. Astrophys.* 467, 1103-1115 (2007).
12. N. J. B. Green et al., *Astron. Astrophys.* 375, 1111-1119 (2001).
13. B. Barzel and O. Biham, *J. Chem. Phys.* 127, 144703-1-144703-12 (2007).
14. D. A. Williams et al., *Astron. Geophys.* 48, 1.25-1.34 (2007).
15. A. S. Ferrarotti and H.-P. Gail, *Astron. Astrophys.* 447, 553-576 (2006).
16. I. Cherchneff, “Dust Formation in Carbon-Rich AGB Stars” in *The Molecular Astrophysics of Stars and Galaxies*, edited by T. W. Hartquist and D. A. Williams, Oxford University Press, Oxford, 1998, pp. 265-283.
17. A. B. C. Patzer, *ASP Conf. Ser.* 309, 301-320 (2004).
18. J. S. Bhatt and I. J. Ford, *Mon. Not. R. astr. Soc.* 382, 291-298 (2007).
19. J. A. Nuth III and F. T. Ferguson, *Astrophys. J.* 649, 1178-1183 (2006).
20. B. E. K. Sugarman et al., *Nature* 313, 196-200 (2006).
21. T. Nozawa et al., *Astrophys. J.* 666, 955-966 (2007).